Investigation on Filament Extrusion of Thermoplastic Elastomer (TPE) for Fused Deposition Modeling

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PREFACE

The market of Fused deposition modelling (FDM), also known as 3D printing, is growing rapidly these years and plastic is the most commonly used material in this method. Hard plastic filament such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) are widely used for different levels of FDM manufacturing. But due to the mechanical property of hard plastic, problems like low flexibility, low deformability and resilience, low vibration absorption capacity, rough surface with low friction will occur to restrict the range of application.

Thermoplastic elastomer (TPE) filament enable the 3D printer to manufacture products with high deformability and excellent surface specialty. Traditional manufacturing method for TPE is injection molding which has numbers of restriction on the shape, precision and variance of the product. With the proper investigation on the TPE filament, FDM method can improve the possibility of the TPE product while preserve the unique characteristic of TPE itself.

In this thesis the whole process of TPE filament extrusion method was investigated from granulate to filament. Key manufacturing parameters for desktop extruder 3devo filament extruder were confirmed through manufacturing and analysis. It is observed that the quality of the filament was mainly determined by the extrusion temperature and extrusion speed. On the other hand, the surface friction of the filament plays an important role in the practical printing feasibility.
This thesis is an investigation of the TPE filament for Fused Deposition Modelling (FDM) manufacturing method. All the investigations aim to optimize the quality of the filament in order to make Thermoplastic Elastomer (TPE) material possible for FDM manufacturing method. Optimization experiments were made to find out key parameters in the extrusion process that determine the quality of the filament. With the optimal parameters, further investigation of the additive content in the TPE granulate was made to solve the current problem of the filament in practical 3D printing, which the high surface friction massively affects the FDM manufacturing feasibility. The filaments were manufactured by the desktop extruder 3devo filament extruder and the surface friction tests were performed on Tribotester™.

Additionally, discussion was made to summarize the pros and cons of TPE material as well as the significance of 3D printing TPE. Potential application and benefits are mentioned for combining the property of TPE and the advantage of FDM manufacturing. Current state-of-art extrusion equipment and FDM technology are also summarized.
ACKNOWLEDGMENT

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In this thesis, Mohammad Nouri contributed in TPE material background information gathering, joining and performing the half time presentation, researching on the extruder and participating some of the experiments and data analyze.

Zicheng Wang contributed in literature researching, experiments design, all the experiments operation and data analyze, equipment maintenance, result analyze, whole thesis writing and improving, presentation preparation and performance.
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1. Introduction

1.1. Background

This thesis mainly investigates on Thermoplastic elastomer (TPE). Thermoplastic elastomers are sometimes known as thermoplastic rubbers. These materials composed of plastics and rubbers have similar properties with these two elements. Composing elastomers and plastics with special methods leads to the production of materials with advantages of constituting components. The new material is known as Thermoplastic elastomer (Modern plastic Encyclopedia, 1994).

Thermoplastic elastomers have all of the advantages of plastics and rubbers. They also have proper deformability characteristics. By Applying load or tensile stress on these materials, they will stretch and after removing load, they will recover their initial configuration. This arises from their elastomeric ability.

Wide variety of these materials made them applicable in different industries such as electronic, house appliances, packing, automobile, etc. These materials are also used for sealing, modifying bitumen and asphalt, producing sports equipment and also for making caps, shoes, leather, gloves, films and cables, dusters, dashboards and bumpers.

With all the advantage TPE has, the 3D printing industry begin to pay more attention to this soft, deformable material. The industry of soft 3D printing filament has been increased rapidly these years. FDM method give more manufacturing possibility comparing to traditional injection molding. But on the other hand, challenge also occurs when 3D printing flexible material. Common pros and cons can be listed in table 1-1.
<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Flexible and soft</td>
<td>• Difficult to print</td>
</tr>
<tr>
<td>• Excellent vibration dampening</td>
<td>• Poor bridging characteristics</td>
</tr>
<tr>
<td>• Long shelf life</td>
<td>• Possibility of blobs and stringing</td>
</tr>
<tr>
<td>• Good impact resistance</td>
<td>• Special extruder nozzle is required</td>
</tr>
</tbody>
</table>

Table 1-1 Pros and cons of flexible 3D printing filament (Simplify 3D®)

Currently on the filament market, the lowest stiffness is 60A shore hardness. Shore hardness usually represents the hardness of rubber, glass and other non-metallic material. Shore-A is the lowest hardness group in the measurement.

1.2. Aim

In this thesis low hardness TPE material was used as raw material during the extrusion which the estimated shore hardness is 55A. The aim of this thesis is to find key parameters for the filament extrusion process, i.e. the extrusion temperature and the extrusion speed. 3Devo Filament Extruder is used to perform the extrusion. 3Devo Filament Extruder is a desktop extruder which can perform filament extrusion in a more flexible condition than traditional extruders. The extruder has four heating units to heat up and melt the granulate before it enters the nozzle. The first aim of the thesis is to find out the optimal temperature and temperature variation between the four heating units.

Extrusion speed is another vital parameter in filament extrusion which directly affect the configuration of the filament. The extrusion speed can be accurate to 0.1 rpm on the extruder. The second aim of the investigation is to find out the optimal extrusion speed which produce the high-quality filament efficiently.

When it comes to flexible filament in 3D printing, one common reason of failure is the filament tends to stuck inside the nozzle so that the material flow stops. One of the main reasons behind this failure is the surface of the filament has too much friction which create a high resistance in the tube inside the nozzle. Additionally, TPE filament has lower material stiffness which fails to transmit the pressure from the rollers to push the molten material in nozzle. Additive granulates were used to lower the surface friction which lead to the third aim of the investigation, finding the optimal percentage of lubrication additive to enhance the manufacturing feasibility.
1.3. Limitation

The extrusion was conducted on a desktop extruder, 3Devo Filament Extruder, and the results are specific to the study material and process settings. When it comes to massive industrial manufacturing the parameters need to be adjusted to fit different environment.

Storage is another important part for flexible material. Certain temperature and humidity are required to keep the filament in a good condition. Flexible material is more likely to lose quality if the filament was exposed high humidity environment. Defect like blobs and bubbles will appear due to the moisture in the filament and the lifespan of the material will shrink as well. Storage condition can be tested through environment simulation equipment which is not available in this investigation.

1.4. Study Environment

This study was finished at Halmstad University. The literature resources were from the school library, official files from TPE material and 3D printing company as well as previous studies on related topic. The optimization experiments were done in mechanical labs in FAB LAB. The mechanical feature tests were done in HGF AB (Halmstad Gummifabrik). The surface friction experiment was done in the mechanical lab at Halmstad University.

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1 HGF AB https://www.hgf.se/sv-SE
2. Method

2.1. Methodology

In this thesis, the main purpose contains two major parts which are filament extrusion optimization and filament printing feasibility investigation. The first part is to produce the high quality TPE filament from granulate through extrusion method. Comparing to other manufacturing method, the extrusion method has the ability to create very complex and very accurate section especially when the materials are brittle (Erik Oberg et al, 2000). It also contains an excellent surface finishing of the final product.

The applied methodology is Key-Parameter-focused test manufacturing. To achieve a complete manufacturing guide for extrusion in the end, one key parameter was set as a variate and the rest parameter was fixed. Once the first optimal parameter was found, it was applied in the following experiment for next parameter. The basic methodology is to create a circulation flow until all the information are confirmed. The sequence of the key parameter experiments is shown in figure 2-1.

![Figure 2-1 Sequence of key parameters experiment](image)

In order to examine the quality of the filament in each experiment extrusion, the diameter tolerance was set as the key indicator. Diameter tolerance represents the fluctuation of the filament diameter during the extrusion. The 3Devo filament extruder is able to measure the diameter of the extruded filament every second during extrusion. Based on the quality and the target diameter the filament puller

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will adjust the pulling speed to get the ideal quality. All the diameter can be collected and analyzed during each extrusion. The diameter measure sensor and the puller are shown in figure 2-2 as follow.

![Figure 2-2 Diameter measure sensor and filament puller](image)

When the extruded filament reached the ideal quality, the printing feasibility was put into test. The most common problem for flexible filament is the inconsistence material flow during the 3D printing process. The material tends to stop extruding from the nozzle of the printer and defect like missing layer or nozzle failure will occur. In this thesis we investigate one aspect of the filament quality that will have negative effect for the printing feasibility which is the surface friction. Special lubricant additive was added in different amount to reduce the surface friction. The coefficient of friction for each sample was also measured on the special force analysis equipment 3 Tribotester™ from InS Thai.

In the end of quality evaluation of the filament, the optimal extrusion result will be put into practical 3D printing test on the printer 4 Flashforge Dreamer with a special nozzle for flexible material (5 Flexion Extruder). The practical 3D printing process will be evaluated again based on several aspects such as the consistence of the material flow, surface quality and layer consistence of the test piece. The

3 Tribotester https://ins-sciences.com/en/

4 Flashforge dreamer http://www.flashforge.com/

5 Flexion Extruder https://flexionextruder.com/
overview of the investigation process and methodology is shown in figure 2-3 as follow.

\[\text{Figure 2-3 Investigation methodology}\]

### 2.2. Extrusion temperature optimization

TPE filament is manufactured by Hot Extrusion working process, which the polymer material in form of pellet is fed into the extruder through a hopper. The materials are then conveyed forward by a feeding screw and forced through a die with opening. Usually granulates TPE are heated at temperature well above their melting or glass transition temperatures. (C.Capone et al, 2007) Information of
commonly used TPE raw material from the market can be found in Appendix 4. Basic manufacturing guidance of *Dryflex UV 602831*, which is one of the most commonly used TPE material from HEXPOL TPE AB, is shown in table 2-1.

<table>
<thead>
<tr>
<th>Processing Temperatures</th>
<th>Injection Molding</th>
<th>Extrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder Temperatures(^\circ C)</td>
<td>180-250</td>
<td>180-230</td>
</tr>
<tr>
<td>Mold Temperatures</td>
<td>30-60</td>
<td></td>
</tr>
<tr>
<td>Predrying</td>
<td>Absolutely necessary 2 hours at 80(^\circ)C dehumidifying dryer</td>
<td></td>
</tr>
</tbody>
</table>

*Table 2-1 Processing temperature for Dryflex UV 602831 (HEXPOL TPE AB)*

In the temperature optimization experiment, the temperature range was set between 180\(^\circ\)C to 230\(^\circ\)C. 3Devo Filament Extruder contains four heating units from the feeding zone to the nozzle. During which the granulate undergo feeding, transitioning and metering before being extruded. Figure 2-4 shows the display screen from the extruder where the temperature can be set.

![Display screen with temperature setting](image)

When the melted TPE passing through the heaters, the regulation of the heater may also affect the quality of the filament. In 3Devo Filament Extruder there already exists some presets temperature and speed for commonly used material such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). According to the preset most of the material has an increasing temperature regulation which means the temperature keep increasing from heater 4 to heater 1. But the material

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Nylon has different regulation which the temperature increases sharply from heater 4 to heater 3 and decrease twice to heater 1. To make sure the investigation covers all the aspects as well as make full use of the four-heater system of 3Devo Filament Extruder. Two groups of temperature regulations were put into test and analyze. The temperature settings are shown in table 2-2. All the other elements are kept in accordance.

<table>
<thead>
<tr>
<th>Invariant</th>
<th>Extrusion speed: 2RPM; Fan speed: 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pattern 1</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H4/°C</td>
</tr>
<tr>
<td>185</td>
<td>190</td>
</tr>
<tr>
<td>210</td>
<td>215</td>
</tr>
<tr>
<td>225</td>
<td>230</td>
</tr>
<tr>
<td><strong>Pattern 2</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H4/°C</td>
</tr>
<tr>
<td>160</td>
<td>170</td>
</tr>
<tr>
<td>185</td>
<td>195</td>
</tr>
<tr>
<td>210</td>
<td>220</td>
</tr>
</tbody>
</table>

*Table 2-2 Design of the temperature optimization experiment*

2.3. **Extrusion speed optimization**

The quality of TPE filament is more affected by the extrusion speed comparing to other solid filaments. Due to the long cooling down time high quality filament usually comes with slow and steady extrusion speed. In the extrusion speed optimization experiment, the result from the previous temperature optimization was used and kept in accordance. Outline visual inspection and filament diameter tolerance data were used to indicate the quality of the filament.
2.4. Surface friction test

2.4.1. Lubrication additive

In this investigation, lubrication additive granulates were provided as well from HEXPOL TPE AB. The additive granulates are half transparent small piece with more hardness than the TPE granulates. During extrusion the lubrication additive tends to wrap the surface of the filament and create a thin but smooth surface with lower surface friction. Since the material ratios of lubricant to material is less, the additive does not have any effect on the hardness of the TPE filament so that the filament stays flexible and soft.

According to HEXPOL TPE AB, the standard percentage of the lubrication additive should be 0.25%, 0.5% and 1% in weight. The granulate should be mixed properly before the extrusion. In this thesis, we test the result with several different percentage include 0%, 0.5%, 0.75%, 1% and 2%. Then the extruded filaments were cut into small sample to run the surface friction measurement. Some commonly used flexible 3D printing filaments in the market were also measured to make comparisons. The results from previous optimization experiments were applied as the extrusion setting. To make the result more credible, every sample was taken from the middle of the spooled filament so that they have the least interference from previous extrusion. Two commonly used flexible filament in the market Flexmark 6 from TreeD Filament and TPU-X60 from Diabase Engineering were also tested to make comparisons. The extruded samples and the filaments from the market are shown in figure 2-5.

7 TreeD Filament www.treedfilaments.com

8 DIABASE ENGINEERING http://diabasepe.com/
2.4.2. Surface friction measurement experiment

The purpose of this experiment is to simulate the movement of the filament inside the PTFE tube in the print head, and investigate if the friction additive has influence on the surface friction of the extruded filament, as well as how much surface friction is required to make smooth and high-quality 3D printing piece. The measurements were made on Tribotester™ from InS Thai in the mechanical lab at Halmstad University.

In order to simulate the filament movement inside the 3D printer head, the internal structure of the printing head should be clear. In this thesis, the printing tests were accomplished using 3D printer Flashforge Dreamer with special printing head Flexion Extruder for flexible material in FAB LAB, Halmstad University. The internal structure of the printing head is shown in figure 2-6.
Before the filament was melted and extruded out from the nozzle, it will go through a PTFE Tube inside the printing head (red circled in figure 2-6). PTFE tube stands for Polytetrafluoroethylene tube which is a synthetic material. The tube has a very low coefficient of friction and is commonly used as guide tubes for 3D printers. The friction between the filament surface and the internal cylinder plays in the main resistance during practical 3D printing.

In this thesis an assumption has been made which the internal cylinder and the outside cylinder surface have the same friction and the filaments in this study have a uniform diameter over the length. The test piece will contact the outside cylinder surface and move at a uniform speed in a straight line. The PTFE tube holder is shown in figure 2-7. A length of PTFE tube was taken from the printer head and attached to a holder to connect with the moving part of Tribotester™.
The test piece was fixed on the stationary platform of Tribotester™ as shown in figure 2-8. Then the PTFE tube is kept contact with the filament surface and moved along its length and the data generated is recorded and the coefficient of friction is calculated. The parameter of the friction test is shown in table 2-3.

Figure 2-8 Friction test set up

Figure 2-7 Friction test set up PTFE tube holder

Figure 2-8 Friction test set up
Friction test parameter

<table>
<thead>
<tr>
<th>Positive pressure</th>
<th>Distance of travel</th>
<th>Travel speed</th>
<th>Quantity of test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1N</td>
<td>30mm</td>
<td>3mm/s</td>
<td>3 pieces/group</td>
</tr>
</tbody>
</table>

Table 2-3 Friction test parameter

During each test the PTFE tube travels for 10 seconds, from which 7 seconds of the consist data of coefficient of friction is considered for calculations. Later three test pieces in each group are averaged again as the final data for one group. To avoid distortion/buckling of the filament during tests, the friction test parameter, pressure is kept at 1N.

2.5. Quality evaluation

In this thesis, the main purpose is to investigate the whole extrusion process to find out the optimal results. Every extrusion process was recorded through the software Arduino, integrated with the extruder during each extrusion. Data was collected every second and summarized into line chart. From the line chart it is easy to tell the diameter tolerance of the whole process to select the better parameter.

To make the data reliable, the data collection starts when the filament was extruded constantly and steadily. Besides, each group of experiment was extruded more than 2500s to reduce interference from other factors. In the end, a consistent 1000-seconds sample data was extracted, from which the extremes were wiped out and the average and the standard deviation was calculated and summarized into histogram. The average shows the overall extrusion quality and the standard deviation reflects the fluctuation of the extrusion.

As for the friction test, the final data for each test group of different percentage of lubrication additive will be summarized and compared with the flexible filament

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9 Arduino http://www.arduino.cc
from the market. Then the extruded filament will be used to do practical 3D printing to evaluate the printing feasibility.
3. Theory

3.1. Additive Manufacturing and Fused deposition manufacturing

Additive Manufacturing (AM) is an appropriate name to describe the technologies that build 3D objects by adding layer-upon-layer of material, whether the material is plastic, metal, concrete etc. (additivemufacturing.com, 2019). Additive manufacturing is widely used in automobile, aeronautics and astronautics, construction, medical devices and home application industries. The application fields of additive manufacturing from Grand View Research is shown in figure 3-1.

![Figure 3-1 US 3D printing market forecast by year, 2014-2025 (Grand View Research, market research report, 2017)](image)

Fused deposition modeling (FDM) is one of the Additive Manufacturing methods which heat the filament material until melt, then proceed the layer-by-layer AM process. It can also be called Fused Filament Modeling (FFL). The main process of FDM is similar as AM process which the 3D model was input to the FDM printer and was analyzed and sliced into layers. The thickness of the layer was decided by the user. A spool of printing filament is drawn through the extruder head which heats the filament to a semi-molten state. The extruder head (or the build platform) is able to move around in the X-Y plane creating a 2D slice of the required part. Once the first layer is complete, the extruder head (or the build platform) will move...
in the Z direction, to enable a second layer of 2D material to be applied on top of 
the first. The semi-molten state of the material allows adjacent layers to fuse 
together forming the 3D solid layer by layer (Tessa Jane Gordelier et al, 2019). FDM 
has been recognized as one of the most economical additive manufacturing 
technologies (Sunpreet Singh, et al, 2017). With the significant increase in sales, 
fused deposition modeling (FDM) printers are now the most prevalent 3D printer 
on the market (Tessa Jane et al, 2019).

3.2. TPE and TPS

Thermoplastic Elastomer (TPE) are a family of rubber like materials that combine 
the characteristics of rubber with the recyclability and processing advantages of 
plastics. (HEXPOL TPE AB, 2019). TPE has special structural features which contains 
both thermoplastic structure and elastomer structure. The thermoplastic structure 
provides the processing characteristics of plasticity and the elastomer structure 
provides the elasticity. This remarkable characteristic and their huge commercial 
development in the last decades, make TPE an intensively investigated class of 
material, both in industry and academia (Tommaso Crisenza, 2012).

TPS (TPE with Styrenic block copolymer) is one of the six generic classes of TPEs 
which based on SBS or SEBS (HEXPOL TPE AB). SBS is based on two-phase block 
copolymer with hard and soft segments. The styrene end blocks provide the 
thermoplastic properties and the Butadiene mid-blocks provide the elastomeric 
properties. SBS is the highest volume TPS material produced and is commonly used 
in footwear, adhesives and low specification seals and grips. SBS, when 
hydrogenated, becomes SEBS. SEBS is characterized by improved heat resistance, 
mechanical properties and chemical resistance, making them ideal choice for 
outdoor and long service span application (HEXPOL TPE AB).

3.3. Filament extrusion

Extrusion is a very important part of the plastic manufacturing industry. To extrude 
means to push or to force out. Material is extruded when it is pushed through an 
opening. The part of the machine containing the opening through which the 
material is forced is referred to as the extruder die. Materials is usually extruded 
in the molten state. In this case, the extruder performs melting as an additional 
function. (Chris Rauwendaal, 2014) The first machine for extrusion of 
thermoplastic materials was built around 1935 by Paul Troester in Germany (M.
Kaufman, 1969). After years of development, very high-speed (1000-1500 RPM) single screw (50-70mm) extruders have been commercially available since about 2005-2010. This is one of the most significant developments in single screw extrusion over the past several decades which boosted the output rate (Chris Rauwendaal, 2014).

In the 3D printing filament extrusion industry, the industrial scale manufacturing capacity for one extruder is usually more than 18kg/hour (Richard Moller, 2017). The leading filament manufacturer include Advanc3D Materials® (Germany), Setup Performance SAS® (France), Print-Rite® (China), etc. Widely used industrial filament production equipment include Saoao® SESI-35/28, Yuanjin® YJ35, Dinglong® DL50 (China.cn, 2019) etc.

### 3.3.1. 3Devo Filament extruder Composer 450

The desktop extruder used in this investigation is from 3devo company from the Netherlands. The model of the extruder is 3devo filament maker Composer 450 (as shown in figure 3-2 left). The composer is desktop filament maker designed for effortless operation with automatic neat spooling (3devo.com, 2019).

![Figure 3-2 3devo filament maker Composer 450 (left) Internal structure of the extruder (right)](image)

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10 3devo filament maker composer 450 http://3devo.com/product/composer-450/
Figure 3-2 (right) shows the internal structure of the extruder. The feeding of the filament was operated by a nitride hardened screw with swappable design for advanced compounding. From the hopper to the extruding nozzle, there are four independent controllable heaters to control the temperature (up to 450°C) during feeding, transitioning and metering.

During the extrusion, the extruder can be connected with the software Arduino for real-time extrusion data analysis. The extruder was designed to have a unique vertical extrusion setup to ensure the precise roundness and accurately guides the filament to the spool (3deco.com, 2019). Figure 3-3 (left) shows a dual air-cooling system is applied with adjustable fan speeds and positions to ensure the optimal cooling setting for the extruded material. Figure 3-3 (right) shows the optical diameter sensor and the dynamic puller system which work together to achieve a diameter precision.

![Figure 3-3 Dual air-cooling fan (left) & optical diameter sensor and dynamic puller system (right)](image)

### 3.4. Surface friction impact on Printing feasibility

To 3D print flexible and ultra-flexible filaments with shore hardness 70A or less, special print heads might be required (Flexion extruder is used in this thesis). Comparing to the flexible material from the current market, extruded TPE has two disadvantages in practical printing which is the low stiffness and high surface friction. The lower stiffness property of the filament fails to transmit the pressure from the rollers to push the molten material out of the nozzle. The lower stiffness gives TPE high flexibility for special usage which is expected to be preserved. But the drawback during the manufacturing process also need to be overcome.

The surface friction on the other hand also causes the filament to stuck and drag inside the print head which finally leads to inconsistence extrusion during printing. The PTFE tube inside the print head has very low coefficient of friction itself and is
also able to self-lubricate during contact with the filament. Due to the inevitable movement and vibration inside the print head the filament is very likely to have large contact area with the internal surface of the PTFE tube. Due to variable speed during printing, the surface friction of the filament tends to cause more defect during printing and eventually leads to defect in product. The surface friction is reduced by mixing lubrication additive inside the granulate which forms a thin layer to cover the external cylinder of the filament to reduce the friction. The friction additive will not affect the hardness of the final product so that the products are able to keep the low-hardness feature.

3.4.1. Tribotester CETR

*Tribotester CETR* (figure 3-4) is a state-of-art Tribological Station with interchangeable modules allowing it to perform many tests (Ins Thai, 2018). The tribotester contains a 6D Force-Torque sensor which can measure the force and the torque on X, Y and Z axis (force from 1N to 1000N, torque from 0.1N.m to 20N.m). In this investigation, the purpose is to measure the coefficient of friction of each filament sample based on the general equation for friction force \( F = \mu F_N \). The positive force will be given in -Z axis and the movement will be on the horizontal level. Tribotester CETR is fully programmable and computer controlled and the result will be formed as line chart automatically after the test is done.

*Figure 3-4 Tribotester CETR*
3.5. Significance of TPE extrusion

TPE plastic contains several qualities that make it a high-performance material among the flexible plastic. The advantages can be listed as follow (Levensalor, Alex, 2016).

- High intensity and rebound resilience.
- Environmentally friendly and nontoxic.
- Easy to recycle and can be inject easily over molding with PC, PS or ABS to provide a soft surface touch.
- Outstanding dyeing property and vibration dampening.
- Processing efficiency, TPE only require one-sixth of the molding time comparing to thermoset.

With all the properties above TPE obtain a wide range of application which covers soft-touch applications, food packaging children’s tableware, sports equipment, medical and healthcare applications and perfect sealing rings. Due to the economic consideration and growing environmental requirement in the plastic industry, TPE as an environmentally friendly material, has wide and substantial market. (B.H.Ter Meulen, 1983)

On the contrary, TPE has several disadvantages which hold it back from being widely used. The first one is the cost of the raw material is very high which increase the cost of the manufacturing. (TPE-processing-guidence-Chinese, 2017). The traditional injection molding method decrease the manufacturing flexibility of TPE and restrain the potential of it. The first significance of TPE extrusion is to make FDM method possible for TPE and allow customized and modified products as well as make full use of the material in order to lower the cost.

On the other hand, TPE extrusion enable Rapid Prototyping of TPE material by using FDM method to test designed product. Nowadays, all 3D printers in the $1000-4000 range are targeted at SMEs and entrepreneurs in need of rapid prototyping (Thierry Rayna et al, 2016). Due to the low temperature resistance, the quality of TPE products decrease massively with increasing temperature which limited the application. Rapid Prototyping is the best solution to test whether the products reach the expected condition. Only with high quality TPE filament can make Rapid Prototyping possible.
Lastly, TPE material has very high demand for the injection mold (TPE-processing-guidence-Chinese, 2017). For example, the draft angle of the mold must be higher than three degrees which increase the cost of the mold as well as restrain the manufacturing flexibility. The internal surface of the mold requires special treatment like aerosol honing, which also increase the cost and maintenance effort. Traditional demold mechanism also damage the surface of the product so that air-pressure demold is required in some special design. With the development of FDM method all the extra mold cost will be eliminated and the advantages of TPE can be fully used.
4. Result

4.1. Result of temperature optimization

As earlier mentioned in section 2.2, in the temperature optimization experiment, two kinds of temperature variation were investigated. The first temperature pattern (pattern 1) is similar to the preset of Nylon 12 material in the extruder and the temperature variation from heater 4 to heater 1 is increase-decrease-decrease. The filament detailed diameter tolerance results for three groups of experiments can be seen in Appendix 1. The experiment groups in further article were designated after the pattern and the temperature of heater 1, e.g. pattern 1, 180° C. The average results and the standard deviation for each temperature of pattern 1 is shown in figure 4-1.

![Average diameter thickness Pattern 1](image)

*Figure 4-1 Average and standard deviation for filament thickness in pattern 1*

In temperature optimization experiment pattern 2 the variation of temperature from heater 4 to heater 1 is increase-increase-increase which is also applied by most of other materials during filament extrusion. The average results and the standard deviation for each temperature of pattern 2 is shown in figure 4-2.
With the target filament thickness of 1.75mm and the data analyze, pattern 2, 205 ℃ (1.749±0.044m) stands out as the optimal extrusion result. The extrusion process was smooth and consist and during the visual inspection, the cross-sectional view of the filament appears to have good roundness appearance.
4.2. Result of extrusion speed optimization

Before the extrusion speed optimization, the previous experiment was performed in 2 RPM which is the lowest speed of the extruder. Previous temperature optimization result is used as temperature setting. Commonly recommended extrusion speed is 3.5 RPM. In the speed optimization experiment the speed increase by 0.2 RPM between every group. The filament diameter tolerance result is shown in figure 4-3. Detailed diameter tolerance chart is shown in Appendix 2.

\[ \text{Figure 4-3 Result of extrusion speed optimization} \]

From the result six groups shared the similar average and standard deviation. But the actual quality of the filament started to drop after the extrusion speed is higher
than 2.4RPM. Filament defect such as belt defect (out-of-roundness) and sticking on the pulling roller occurs. The defects are shown in figure 4-4.

The reason of these defect is the high extrusion speed does not allow the filament get enough cooldown before feeding. Considering the quality and the time efficiency, S3 (2.4RPM) is the optimal extrusion speed.
4.3. Result of lubrication additive influence

Lubrication additive tests were taken among five groups of extruded filaments and two commonly used flexible filament in the market, *Flexmark 6* and *TPU X60* (shore hardness 60A). Three test sample were measured in each group. The coefficient of friction among all the test groups are shown in figure 4-5. Detailed measurement diagrams are shown in Appendix 3.

![Coefficient of friction](image)

*Figure 4-5 Coefficient of friction measurement result (lubricant ratio)*

The lubrication additive affected the surface friction of the filament as expected. The surface friction drops linearly deceleration with the increase of lubrication additive. The lubricant additive permeates to the external surface and form a thin smooth layer to reduce the surface friction. The filaments were also put into practical test printing to examine the printing feasibility.
The filament with no lubrication additive was not able to be fed into the nozzle. Only until 0.75% of lubrication additive could the nozzle on the printer started to extrude. The test was taken with a very low printing speed (15mm/s) and low layer thickness (0.1mm). The test print result can be shown in figure 4-6.

![Figure 4-6 Test print piece 0.5% additive (left) and 2% additive (right)](image)

The lower additive percentage filament still met the same problem which is the inconsistency of extrusion during printing. The friction between the filament and the PTFE tube might be too high and the material stopped extruding after few layers of printing. With the high percentage of lubricant, the defect decreased on some level but still would occur over time. If the printing piece can be 3D printed in a short period of time, the filament might have better extrusion from the 3D printing head and to print some flat test pieces with very good quality (as shown in figure 4-7).

![Figure 4-7 Flat test piece with ideal quality](image)
5. Conclusion

5.1. Conclusion

In this investigation the optimal extrusion parameters have been found from scientific method which covers most possibilities in the limited time.

- The optimal extrusion temperature for extruding TPE-SEBS in 3Devo Filament Extruder is found to be $185, 195, 200, 205^\circ\text{C}$ (from heater 4 to heater 1).

- The optimal extrusion speed is found to be the 2.4 RPM which maintain the high roundness and consistence as well as maximize the productivity.

The lubrication test reaches the expectation with the lubrication additive covers the surface of the filament and linearly reduce the surface friction with the increase in percentage. The print feasibility increases with the percentage of lubrication additive. Special printer setting and printing head are required to reach the highest quality. The most commonly defect of the printing process is the inconsistence of extrusion. Too much surface friction combined with low stiffness of the material is the main cause of this defect. The filament is able to finish printing flat, low-height products with promising quality.

5.2. Recommendation to further investigation activities

In this thesis most parameter in the manufacturing process have been confirmed. However, storage environment is another critical aspect which massively affect the quality of flexible filament. Constant temperature and moisture cabinet can be applied in further investigation to control entire manufacturing cycle of the filament.

On the other hand, TPE has high recyclablility which has not been tested in the investigation. Further investigation can focus of how to recycle the low-quality filament or failed printed piece to make the material more economical.

When it come to the print feasibility, this investigation focuses only on one possible cause which is the surface friction. Other aspects include print head or the
parameters of the printer during manufacturing have not been investigated. Each test setting could be recorded and analyzed to find out the identical setting for the extruded filament.
6. Critical review

In this investigation the original purpose which is to find out the optimal parameter to extrude TPE filament with ideal quality has been achieved. The investigation made full use of the raw material and all the test are performed with the most representative part of the extruded filament.

The lubrication additive reduced the coefficient of friction of the surface to 0.168 (with 2% of lubrication additive) but still higher than the TPU X60 (0.128) from the market. Higher percentage of lubrication additive could be added to make comparisons in the same level of coefficient of friction. But at the same time, higher percentage of lubricant additive might lead to the change of the material property. The balance between print feasibility and the material property should be considered.

From the social aspect, one of the prominent areas of increased interest in 3D printing is in the realm of education: fabrication tools are becoming available to college undergraduate and high school students (Michael Eisenberg, 2013). 3D printed TPE products are nontoxic and can make almost everything. These advantages make it the perfect choice for education tools for students especially in biology or chemistry.

From economical aspect, TPE filament extrusion increase the possibility of rapid prototyping. Companies which produce flexible product will have more control and prediction of their new innovation product with 3D printed TPE prototype. The positive affect on the value proposition component of the new product allows the company to release new products more quickly. (Thierry Rayna, Ludmila Striukova, 2016). Customized souvenirs are another booming aspect of 3D printing industry. (Michael Eisenberg, 2013). 3D printed TPE are flexible and have different properties and can be used in different applications. TPE material could be an alternative of PLA or ABS.

TPE filament in FDM is not as cost effective as other common filament due to the high cost of the material and special printer requirement. But on the other hand, TPE can be 100% recycled. From the economical aspect the usage of TPE filament and the recycle methods should be further discussed and improved to make full use of the advantages of the material specialty and the feature of FDM.
Reference


[18] Tessa Jane Gordelier, Philipp Rudolf Thies, 2019, Optimizing the FDM additive manufacturing process to achieve maximum tensile strength: a
state-of-the-art review, University of Exeter, Penryn, UK.


Appendix

Appendix 1. Filament diameter tolerance diagram in temperature optimization

The temperature is labeled from heater 4 to heater 1.

1.1. Pattern 1 (increase-decrease-decrease)

Figure 8-1 Filament tolerance under 185,190,185,180 °C

Figure 8-2 Filament tolerance under 210,215,210,205 °C
1.2. Pattern 2 (increase-increase-increase)
Figure 8-6 Filament tolerance under 210, 220, 225, 230 °C
Appendix 2. Filament diameter tolerance diagram for extrusion speed optimization

Figure 8-7 Filament tolerance under 2RPM

Figure 8-8 Filament tolerance under 2.2RPM

Figure 8-9 Filament tolerance under 2.4RPM
Figure 8-10 Filament tolerance under 2.5RPM

Figure 8-11 Filament tolerance under 2.8RPM

Figure 8-12 Filament tolerance under 3RPM
Appendix 3. Friction test data

Figure 8-13 TPE 0% lubrication additive

Figure 8-14 TPE 0.5% lubrication additive
Figure 8-15 TPE 0.75% lubrication additive

Figure 8-16 TPE 1.0% lubrication additive
Figure 8-17 TPE 2.0% lubrication additive

Figure 8-18 TPU X60 (70A)
Figure 8-19 Flex Mark6
Appendix 4. Basic properties of TPE-SEBS

**Dryflex UV 602831 (TPS-SEBS)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Typical Value</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>Shore A</td>
<td>60±3</td>
<td>ISO 868 (3 sec.)</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>g/cm³</td>
<td>0.99</td>
<td>DIN EN ISO 1183-1(A)</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>MPa</td>
<td>5.6</td>
<td>DIN 53504(S2-cross)</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>%</td>
<td>603</td>
<td>DIN 53504(S2-cross)</td>
</tr>
</tbody>
</table>

*TPS Dryflex UV 602831 Properties (HEXPOL TPE AB)*
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